

1 WHAT IS CLAIMED IS:

- 2
- 3 1. A method of controlling movement in a dynamic system which can be expressed
- 4 in terms of both rigid and flexible modes, the method comprising the steps of:
- 5 generating a rigid body input for the dynamic system;
- 6 processing the rigid body input so as to produce a processed input which
- 7 compensates for vibrations in the flexible mode of the system; and
- 8 applying the processed input to control the dynamic system.
- 9
- 10 2. A method according to Claim 1, wherein the generating step comprises (i)
- 11 creating a model of the rigid mode of the dynamic system based on a modal
- 12 analysis, and (ii) determining the rigid body input based on the modal analysis.
- 13
- 14 3. A method according to Claim 1, wherein the rigid body input corresponds to a
- 15 fundamental limiting parameter of the system, the fundamental limiting parameter
- 16 of the system comprising a first parameter of the system to enter into saturation.
- 17
- 18 4. A method according to Claim 3, wherein the processing step processes the rigid
- 19 body input in accordance with a system vibration limiting constraint and a system
- 20 sensitivity constraint.
- 21
- 22 5. A method according to Claim 4, wherein the system vibration limiting and
- 23 sensitivity constraints reduce vibration during movement of a component of the
- 24 dynamic system by less than 100%.
- 25
- 26 6. A method according to Claim 1, wherein the processing step processes the rigid
- 27 body input in accordance with one or more constraints that are a function of a
- 28 movement distance of a component of the dynamic system.
- 29

- 1 7. A method according to Claim 1, wherein the processing step processes the rigid
2 body input in accordance with a system vibration limiting constraint only.
3
- 4 8. A method according to Claim 1, wherein the processing step shapes the rigid body
5 input using a predetermined shaping function.
6
- 7 9. A method according to Claim 8, wherein the rigid body input includes both
8 transient portions and a steady state portion; and
9 wherein only the transient portions of the rigid body input are shaped in
10 accordance with the predetermined shaping function.
11
- 12 10. A method according to Claim 1, wherein the processing step processes the rigid
13 body input by filtering the input using filters having zeros which are substantially
14 near poles of the system.
15
- 16 11. A method according to Claim 1, wherein the processing step processes the rigid
17 body input in accordance with at least one of constraints relating to system
18 thermal limits, system current limits, and system duty cycle.
19
- 20 12. A method according to Claim 1, wherein the processing step processes the rigid
21 body input by determining a movement distance of a component of the dynamic
22 system and modifying the rigid body input based on the movement distance.
23
- 24 13. A method according to Claim 1, wherein the rigid body input comprises a
25 Posicast input.
26
- 27 14. A method according to Claim 1, wherein the rigid body input comprises a
28 symmetric input.
29

- 1 15. A method according to Claim 1, wherein the processing step processes the rigid
2 body input in accordance with a symmetric constraint that varies as a function of
3 at least one of time and position of a component of the dynamic system.
4
- 5 16. A method according to Claim 1, wherein the rigid body input comprises a voltage
6 which has been controlled by controlling current.
7
- 8 17. A method according to any one of Claims 1 to 16, wherein the processing step
9 comprises:
10 identifying system parameters in real-time; and
11 modifying the rigid body input in real-time in accordance with the system
12 parameters identified in the identifying step.
13
- 14 18. A method according to Claim 2, wherein the determining step determines the
15 rigid body input in accordance with an insensitivity constraint.
16
- 17 19. A method according to Claim 2, wherein the model of the system comprises a
18 plurality of equations for the system; and
19 wherein an insensitivity constraint for a particular system parameter is
20 added to the system by taking a derivative of a system equation with
21 respect to the insensitivity constraint and setting the derivative equal to
22 zero.
23
- 24 20. A method according to Claim 2, wherein the model of the system comprises a
25 plurality of equations for the system; and
26 wherein an insensitivity constraint for a particular system parameter is
27 added to the system by setting a series of constraints for different values of
28 the system parameter so as to limit a variation in the system parameter.
29

- 1 21. A method according to Claim 2, wherein the rigid body input is determined in
2 accordance with a feedback signal; and
3 wherein the method further comprises adding a quasi-static correction
4 factor to the feedback signal, the quasi-static correction factor correcting
5 for a deflection in the component during movement.
6
- 7 22. A method according to Claim 2, further comprising determining a center of mass
8 of a component of the dynamic system;
9 wherein the rigid body input is determined in accordance with a feedback
10 signal based on the center of mass of the component.
11
- 12 23. A method of determining plural switch times for a voltage input to a dynamic
13 system having plural modes, the method comprising the steps of:
14 generating a model of the dynamic system based on a modal analysis of
15 each of the plural modes;
16 determining a response of the dynamic system in terms of the modal
17 analysis in the model;
18 determining an expression for a contribution of each of the plural modes to
19 a final location of the system based on a corresponding response, the
20 contribution of each mode of the system being based on switch times for
21 the voltage input;
22 estimating values relating to the plural switch times; and
23 calculating approximations of the values relating to the plural switch times
24 based on the estimated values using the expression for the contribution of
25 each of the plural modes and the modal analysis in the model of the
26 dynamic system.
27
- 28 24. A method according to Claim 23, further comprising the step of re-calculating
29 approximations of the values based on a previous approximation the values.
30

- 1 25. A method according to Claim 24, wherein the re-calculating step is repeated a
2 plurality of times, each time using a re-calculated approximation of the values as
3 the previous approximation of the values.
4
- 5 26. A method according to Claim 23, further comprising the step of generating a table
6 comprising plural switch times;
7 wherein the estimating step comprises estimating the values using the
8 table.
9
- 10 27. A method according to Claim 23, further comprising the step of generating at
11 least one curve corresponding to the plural switch times;
12 wherein the estimating step comprises estimating the values using the at
13 least one curve.
14
- 15 28. A method according to Claim 23, wherein the dynamic system comprise a data
16 storage device; and
17 wherein the voltage inputs comprise voltage inputs to the data storage
18 device.
19
- 20 29. A method according to Claim 23, further comprising the step of performing input
21 shaping on the voltage input after switch times therefor have been calculated.
22
- 23 30. A method according to Claim 23, wherein the estimating step is performed using
24 a parameter estimator.
25
- 26 31. A method of reducing unwanted vibrations in a dynamic system, the method
27 comprising the steps of:
28 determining whether greater than a predetermined level of vibrations will
29 be excited by a system input; and

1 modifying the input to the dynamic system in a case that greater than the
2 predetermined level of vibrations will be excited, where the input to the
3 dynamic system is modified so as to reduce the level of vibrations in the
4 system to less than the predetermined level of vibrations
5

6 32. A method according to Claim 31, wherein the modifying step comprises using at
7 least one of an input shaper, an inverse shaper, and a filter in order to modify the
8 input to the dynamic system.
9

10 33. An apparatus which controls a dynamic system that can be expressed in terms of
11 both rigid and flexible modes, the apparatus comprising:
12 a memory which stores computer-executable process steps; and
13 a processor which executes the process steps stored in the memory so as
14 (i) to generate a rigid body input for the dynamic system, (ii) to process
15 the rigid body input so as to produce a processed input which compensates
16 for vibrations in the flexible mode of the system, and (iii) to apply the
17 processed input to control the dynamic system.
18

19 34. An apparatus according to Claim 33, wherein the processor generates the rigid
20 body input by (i) creating a model of the rigid mode of the dynamic system based
21 on a modal analysis of the system, and (ii) determining an input to the dynamic
22 system based on the modal analysis,
23

24 35. An apparatus according to Claim 32, wherein the rigid body input comprises a
25 fundamental limiting parameter of the system, the fundamental limiting parameter
26 of the system corresponding to a first parameter in the system to enter into
27 saturation.
28

- 1 36. An apparatus according to Claim 35, wherein the processor processes the rigid
2 body input in accordance with a system vibration limiting constraint and a system
3 sensitivity constraint.
4
- 5 37. An apparatus according to Claim 36, wherein the system vibration limiting and
6 sensitivity constraints reduce vibration during movement of the component by
7 less than 100%.
8
- 9 38. An apparatus according to Claim 33, wherein the processor processes the rigid
10 body input in accordance with one or more constraints that are a function of a
11 movement distance of a component of the dynamic system.
12
- 13 39. An apparatus according to Claim 33, wherein the processor processes the rigid
14 body input in accordance with a system vibration limiting constraint only.
15
- 16 40. An apparatus according to Claim 33, wherein the processor shapes the rigid body
17 input using a predetermined shaping function.
18
- 19 41. An apparatus according to Claim 40, wherein the rigid body input includes both
20 transient portions and a steady state portion; and
21 wherein the processor shapes only the transient portions of the rigid body
22 input in accordance with the predetermined shaping function.
23
- 24 42. An apparatus according to Claim 33, wherein the processor processes the rigid
25 body input by filtering the input using filters having zeros which are substantially
26 near poles of the system.
27
- 28 43. An apparatus according to Claim 33, wherein the processor processes the rigid
29 body input in accordance with at least one of constraints relating to system
30 thermal limits, system current limits, and system duty cycle.

- 1
- 2 44. An apparatus according to Claim 33, wherein the processor processes the rigid
- 3 body input by determining a movement distance of a component of the dynamic
- 4 system and modifying the input based on the movement distance.
- 5
- 6 45. An apparatus according to Claim 33, wherein the rigid body input comprises a
- 7 Posicast input.
- 8
- 9 46. An apparatus according to Claim 33, wherein the rigid body input comprises a
- 10 symmetric input.
- 11
- 12 47. An apparatus according to Claim 33, wherein the processor processes the rigid
- 13 body input in accordance with a symmetric constraint that varies as a function of
- 14 at least one of time and position of a component of the dynamic system.
- 15
- 16 48. An apparatus according to Claim 33, wherein the processor processes the rigid
- 17 body input based on a voltage which has been controlled by controlling current.
- 18
- 19 49. An apparatus according to any one of Claims 33 to 48, wherein the processor
- 20 processes the rigid body input by (i) identifying system parameters in real-time,
- 21 and (ii) modifying the input in real-time in accordance with the system parameters
- 22 identified by the processor.
- 23
- 24 50. An apparatus according to Claim 33, wherein the processor generates the rigid
- 25 body input in accordance with an insensitivity constraint.
- 26
- 27 51. An apparatus according to Claim 50, wherein the model of the system comprises a
- 28 plurality of equations for the system; and
- 29 wherein an insensitivity constraint for a particular system parameter is
- 30 added to the system by taking a derivative of a system equation with

1 respect to the insensitivity constraint and setting the derivative equal to
2 zero.

3

4 52. An apparatus according to Claim 50, wherein the model of the system comprises a
5 plurality of equations for the system; and

6 wherein an insensitivity constraint for a particular system parameter is
7 added to the system by setting a series of constraints for different values of
8 the system parameter so as to limit a variation in the system parameter.

9

10 53. An apparatus according to Claim 33, wherein the processor generates the rigid
11 body input in accordance with a feedback signal; and

12 wherein the processor adds a quasi-static correction factor to the feedback
13 signal, the quasi-static correction factor correcting for a deflection in the
14 component during movement.

15

16 54. An apparatus according to Claim 33, wherein the processor determines a center of
17 mass of a component of the dynamic system; and

18 wherein the processor generates the rigid body input in accordance with a
19 feedback signal based on the center of mass of the component.

20

21 55. An apparatus which determines plural switch times for a voltage input into a
22 dynamic system having plural modes, the apparatus comprising:

23 a memory which stores computer-executable process steps; and

24 a processor which executes the process steps stored in the memory so as

25 (i) to generate a model of the dynamic system in terms of a modal analysis

26 each of the plural modes, (ii) to determine a response of the dynamic

27 system in terms of the modal analysis in the model, (iii) to determine an

28 expression for a contribution of each of the plural modes to a final location

29 of the system based on a corresponding response, the contribution of each

30 mode of the system being based on switch times for the voltage input, (iv)

1 to estimate values corresponding to the plural switch times, and (v) to
2 calculate approximations of the values corresponding to the plural switch
3 times based on the estimated values using the expression for the
4 contribution of each of the plural modes and the modal analysis in the
5 model of the dynamic system.
6

7 56. An apparatus according to Claim 55, wherein the processor re-calculates
8 approximations of the values based on a previous approximation of the values.
9

10 57. An apparatus according to Claim 56, wherein the processor re-calculates
11 approximations of the values a plurality of times, each time using a re-calculated
12 approximation of the values as the previous approximation of the values.
13

14 58. An apparatus according to Claim 55, wherein the processor generates a table
15 comprising plural switch times; and
16 wherein the processor estimates the values using the table.
17

18 59. An apparatus according to Claim 55, wherein the processor generates at least one
19 curve corresponding to the plural switch times; and
20 wherein the processor estimates the values using the at least one curve.
21

22 60. An apparatus according to Claim 55, wherein the dynamic system comprises a
23 data storage device; and
24 wherein the voltage inputs comprise voltage inputs to the data storage
25 device.
26

27 61. An apparatus according to Claim 55, further comprising the step of performing
28 input shaping on the voltage input after switch times therefor have been
29 calculated.
30

- 1 62. An apparatus which reduces unwanted vibrations in a dynamic system, the
2 apparatus comprising:
3 a memory which stores computer-executable process steps; and
4 a processor which executes the process steps stored in the memory so as
5 (i) to determine whether greater than a predetermined level of vibrations
6 will be excited by an input to the system, and (ii) to modify the input to
7 the dynamic system in a case that greater than the predetermined level of
8 vibrations will be excited, where the processor modifies the input to the
9 dynamic system so as to reduce the level of vibrations in the system to less
10 than the predetermined level of vibrations.
11
- 12 63. An apparatus according to Claim 62, wherein the processor modifies the input to
13 the dynamic system using at least one of an input shaper, an inverse shaper, and a
14 filter.
15
- 16 64. A method of controlling a dynamic system in accordance with an input that is a
17 function of time so as to reduce unwanted vibrations in the system, the method
18 comprising the steps of:
19 generating a model of the dynamic system, the model defining system
20 position in terms of both time and a system input, and the model
21 constraining the system in accordance with one or more constraints
22 relating to the unwanted vibrations;
23 determining an input to the dynamic system which reduces the unwanted
24 vibrations based on the model generated in the generating step; and
25 controlling the dynamic system in accordance with the input determined in
26 the determining step.
27
- 28 65. A method according to Claim 64, wherein the model of the system comprises a
29 partial fraction expansion of third order equations that define the system.
30

- 1 66. A method according to Claim 65, wherein the partial fraction expansion equations
2 comprise:

$$Finalpos = \sum_{i=1}^N V_i A \Delta t$$

$$0 = \sum_{i=1}^N V_i \frac{Ab}{b-a} (e^{-a(T_{end}-T_i+\Delta t)} - e^{-a(T_{end}-T_i)})$$

$$0 = \sum_{i=1}^N V_i \frac{Aa}{a-b} (e^{-b(T_{end}-T_i+\Delta t)} - e^{-b(T_{end}-T_i)}),$$

3
4 where Finalpos is the final position of a component of the dynamic system, T_{end}
5 corresponds to a time at which Finalpos is reached, A, a and b are based on the
6 system parameters, V_i are voltage inputs to the system, T_i are the times at which
7 V_i are input, and Δt is a time interval at which V_i are input.

- 8
9 67. A method according to Claim 64, wherein the input determined in the determining
10 step comprises the fundamental limiting parameter of the system, the fundamental
11 limiting parameter corresponding to a first parameter in the system to enter into
12 saturation.

- 13
14 68. A method of using a current command to control a system having voltage as a
15 physical limiting parameter, where the system includes a current controller
16 connected to a power supply, the method comprising the steps of:
17 inputting a current command to the system;
18 shaping the current command using a unity magnitude shaper so that the
19 current controller in the system goes into saturation; and
20 supplying voltage to the system from the power supply via the current
21 controller in saturation.
22

- 1 69. A method of controlling a dynamic system having one or more feedforward
2 inputs, where one of the feedforward inputs corresponds to a fundamental limiting
3 parameter of the system, the method comprising the steps of:
4 altering a form of a feedforward input that corresponds to the fundamental
5 limiting parameter of the system so as to reduce unwanted dynamics of the
6 system.
7
- 8 70. A method according to Claim 69, further comprising the step of determining the
9 fundamental limiting parameter of the system by identifying a first parameter of
10 the system to enter into saturation.
11
- 12 71. A method according to Claim 69, wherein the altering step comprises shaping the
13 feedforward input.
14
- 15 72. A method according to Claim 71, wherein the shaping is performed using Input
16 ShapingTM.
17
- 18 73. A method according to Claim 71, wherein the shaping is performed using one or
19 more filters.
20
- 21 74. A method according to Claim 71, further comprising the steps of:
22 identifying any nonlinear elements in the system;
23 wherein the shaping is performed after any nonlinear elements identified
24 in the identifying step.
25
- 26 75. A method according to Claim 69, wherein the altering step comprises pre-
27 saturating the feedforward input and then shaping the feedforward input.
28
- 29 76. A method according to Claim 69, wherein the dynamic system comprises a data
30 storage device system; and

- 1 wherein the fundamental limiting parameter comprises voltage.
- 2
- 3 77. A data storage device system having one or more feedforward inputs, where one
- 4 of the feedforward inputs corresponds to a fundamental limiting parameter of the
- 5 system, the system comprising:
- 6 a memory which stores computer-executable process steps; and
- 7 a processor which executes the process steps stored in the memory so as to
- 8 alter a form of a feedforward input that corresponds to the fundamental
- 9 limiting parameter of the system so as to reduce unwanted dynamics of the
- 10 system.
- 11
- 12 78. A system according to Claim 77, wherein the processor executes process steps so
- 13 as to determine the fundamental limiting parameter of the system by identifying a
- 14 first parameter of the system to enter into saturation.
- 15
- 16 79. A system according to Claim 77, wherein the feedforward input is altered by
- 17 shaping the feedforward input.
- 18
- 19 80. A system according to Claim 79, wherein the shaping is performed using Input
- 20 ShapingTM.
- 21
- 22 81. A system according to Claim 79, wherein the shaping is performed using one or
- 23 more filters.
- 24
- 25 82. A system according to Claim 79, wherein the processor executes process steps so
- 26 as to identify any nonlinear elements in the system;
- 27 wherein the shaping is performed after any nonlinear elements identified
- 28 by the processor.
- 29

- 1 83. A system according to Claim 77, wherein the processor alters the feedforward
2 input by pre-saturating the feedforward input and then shaping the feedforward
3 input.
4
- 5 84. A method of shaping an input to a dynamic system so as to reduce unwanted
6 dynamics in the system, the input to the dynamic system comprising digital data
7 sampled at a predetermined frequency, the method comprising the steps of:
8 identifying system vibrations that occur at the Nyquist frequency for the
9 system, the system vibrations corresponding to a sine wave having two
10 sample points per period; and
11 applying a three-pulse shaper to the input, wherein first and second pulses
12 of the three-pulse shaper are applied at the two sample points in a first
13 period of the input, and a third pulse of the three-pulse shaper is applied at
14 a first sample point in a second period of the input.
15
- 16 85. A method of generating an input to a computer-controlled dynamic system so as
17 to suppress vibrations therein, the dynamic system having a dedicated path solely
18 for a feedforward input from a controller to controlled hardware, the method
19 comprising the steps of:
20 determining a frequency of vibrations to be suppressed;
21 wherein, in a case that the frequency of the vibrations to be suppressed is
22 at or below a servo rate for the dynamic system, the method comprises the
23 steps of:
24 executing servo calculations for the system;
25 determining a servo output based on the servo calculations; and
26 outputting the servo output as the input to the dynamic system; and
27 wherein, in a case that the frequency is above the servo rate for the
28 dynamic system, the method comprises the steps of:
29 determining a trajectory value;
30 shaping the trajectory; and

1 outputting the shaped trajectory as the input to the dynamic
2 system.

3

4 86. A method of generating an input to a computer-controlled dynamic system so as
5 to suppress vibrations therein, the dynamic system having a path by which a
6 feedforward input and other signals are output from a controller to controlled
7 hardware, the method comprising the steps of:

8 executing servo calculations for the system;
9 determining a servo output based on the servo calculations;
10 storing the servo output in a memory;
11 determining a trajectory value for the feedforward input;
12 shaping the trajectory value; and
13 adding the servo output stored in the memory to the shaped trajectory
14 value so as to generate the feedforward input.

15

16 87. A method of controlling a dynamic system using an input command, comprising
17 the steps of:

18 shaping the input command to saturation;
19 inputting the saturated command until a first predetermined condition is
20 detected;
21 shaping a transition of the input command during deceleration from
22 saturation until a second predetermined condition occurs; and
23 following a preset trajectory until the dynamic system comes to within a
24 predetermined proximity of its final state.

25

26 88. A method according to Claim 87, wherein the preset trajectory comprises a curve
27 in a PV table.

28

29 89. A method of generating commands for a dynamic system in a first parameter
30 which maintain a limit in a second parameter, where the second parameter

1 comprises a fundamental limiting parameter of the dynamic system, the method
2 comprising the steps of:

3 determining a response of the second parameter in the dynamic system to
4 a unit command in the first parameter; and
5 generating the command in the second parameter based on the response
6 determined in the determining step.

7
8 90. A method according to Claim 89, wherein the first parameter is current and the
9 second parameter is voltage; and
10 wherein the dynamic system comprises a disk drive.

11
12 91. A method according to Claim 89, wherein the response is determined by
13 iteratively solving a set of equations for the first parameter knowing at least the
14 second parameter.

15
16 92. A method according to Claim 91, wherein the set of equations comprises:

$$\sum_{i=1}^N A_i = 0,$$

17
18 where A comprises amplitudes of the command in the first parameter at each time
19 interval i, and N comprises a last time interval;

$$v_i = C_{vscale} \sum_{j=1}^{i-1} A_j,$$

20
21 where v comprises a system velocity and C_{vscale} is a constant;

$$P_{final} = \sum_{j=1}^N v_i,$$

where P_{final} comprises a final state of the system; and

$$-V_{lim} < \sum_{i=1}^j A_{j-i+1} R_i < V_{lim}, \quad j = 1 \rightarrow N,$$

where R comprises a pulse response of the system to the second parameter and V_{lim} comprises a limit in the second parameter.

93. A method according to Claim 92, wherein A comprises current, V comprises voltage, and R comprises a voltage response of the system.
94. A method according to Claim 92, wherein the values of R(i) are determined by taking a peak value of the system response and sampling values of the system response at subsequent time increments.
95. A method generating commands for a dynamic system in a first parameter (A) which maintain a limit in a second parameter (V), where the second parameter (V) comprises a fundamental limiting parameter of the dynamic system, the method comprising the steps of:
 - determining a values for a command in the first parameter (A) at time intervals (i) based on the following relationship:

$$A(i) = \frac{V_{\max} - \sum_{j=2}^i A(i+1-j) R(j)}{R(1)},$$

where R comprises a pulse response of the system in the second parameter; and
 formulating a command over time in the first parameter (A) based on the
 A(i) values determined in the determining step.

96. A method according to Claim 95, wherein A comprises current and V comprises
 voltage.

97. A method of controlling a dynamic system having vibrations resulting from
 movement, the method comprising the steps of:
 identifying transitions of an input command to the dynamic system; and
 shaping transitions of the input command so as to result in a system
 response to the input command with reduced vibrations.

98. A method of controlling a system to reduce unwanted dynamics using commands
 in both first and second parameters, where the second parameter comprises a
 fundamental limiting parameter of the system, the method comprising:
 commanding the system in the first parameter during a first mode of
 system operation; and
 commanding the system in the second parameter during a second mode of
 system operation.

99. A method according to Claim 98, wherein the system comprises a disk drive;
 wherein the first mode of operation comprises tracking performed by the
 disk drive; and
 wherein the second mode of operation comprises seeking performed by
 the disk drive.

- 1
- 2 100. A method according to Claim 92, 94, and 95, wherein V_{lim} is varied in accordance
- 3 with i.
- 4
- 5 101. A method according to Claims 89 to 95, wherein constraints are added for
- 6 parameter slew rate limits; and
- 7 wherein the generating step generates the command in accordance with the
- 8 added constraints.
- 9
- 10 102. A method of rescaling a vibration-limiting input to a dynamic system, the method
- 11 comprising the step of:
- 12 linearly scaling amplitudes of the vibration-limiting input to produce a
- 13 scaled vibration-limiting input.
- 14